HI-SMART

HI-SMART: HIGHER EDUCATION PACKAGE FOR NEARLY ZERO ENERGY AND SMART BUILDING DESIGN

# MODULE #2

## CHAPTER 1: THERMAL INSULATION OF NEARLY ZERO ENERGY BUILDINGS

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The energetic performance of buildings is largely dependent on the thermal properties of building envelopes, its shape and geometry can be designed for many different purposes such as daylighting, energy saving, energy generation, acoustic....

The purpose of Chapter 2 is to describe basic parameters and parameters applicable to the construction of building envelope. Chapter 2 provides a general overview of the principle of the assessment and design of structures with regard to the energy performance of buildings and energy certification. Chapter 2 deals with the following topics:

1. Selected thermal technical requirements.

2. Thermal insulation materials.

3. Influence of humidity on thermal technical properties of built-in materials.

4. Literature.

## 2.1.1 CERTAIN THERMAL TECHNICAL REQUIREMENTS

The main purpose of thermal protection of buildings is to reduce heat losses through the thermal bridges in the envelope structure and thus reduce the total heat demand for heating. This provides for the standard for the thermal protection of buildings, where the main criterion is the need for heating being the ultimate energetic criterion. To achieve this criterion, it is necessary to calculate the actual heating demand determined by the energy balance method. Based on the requirements, heat losses through ventilation and thermal bridges need to be reduced . These factors generally have the most significant impact on the overall balance. The heat demand Qh, expressed in kWh, is the calculated heat that must be supplied to to maintain the required temperature in space. It is therefore the heat that an ideal heating system should supply during a given heating period.

The properties of the heating system and the method of preparation of this heat are not included. When determining the heat demand QH, the heat balance is assumed to cover heat losses and gains (Fig. 2.1.1). Outdoor temperature, indoor temperature, indoor gains and solar gains are defined by boundary conditions.

The balance equation is used to calculate the heat demand for heating. In the past, some calculation methods neglected the influence of heat gains in the balance equation. The total demand for heating was only a function of the heat loss of the building from the heated spaces. This type of calculation is used to design a heat source.

$Q_H = Q_T + Q_V - \eta(Q_i + Q_s) = Q_L - \eta(Q_g)$ (2.1)

whereas:

$Q_T$ is needed to cover heat losses by heat transfer through the envelope structures of the heated space in kWh,
$Q_V$ heat demand to cover heat losses by ventilation in kWh,
$Q_i$ heat gains to the heated space from internal sources in kWh,
$Q_s$ heat gains in the heated space from solar radiation behind the glazing of the building in kWh,
η heat gain utilization factor,
$Q_L$ heat demand to cover the total heat loss of the building in kWh,
$Q_g$ total heat gains of the building in kWh.

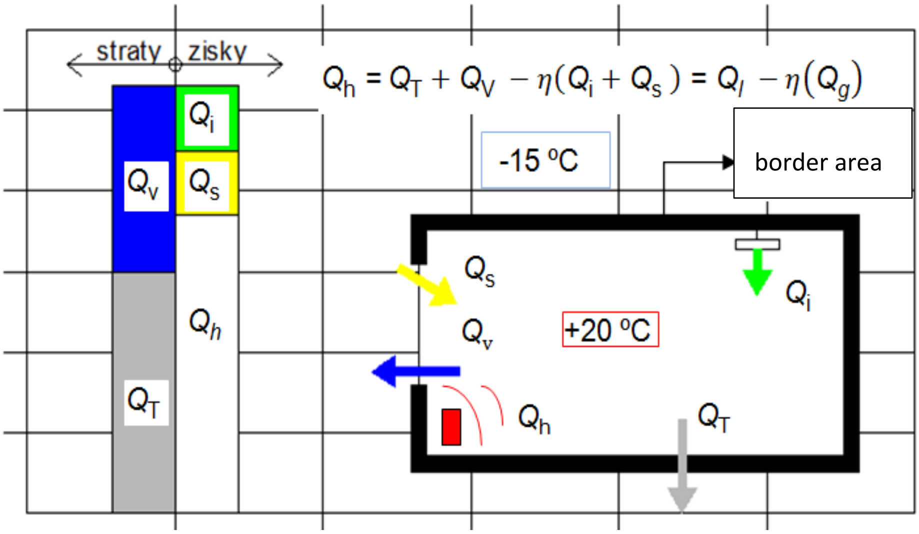


Fig. 2.1.1 Energy need for heating factors

The requirements for the heat transfer coefficient, that are directly related to the energy demand, are set in STN 73 0540: 2+ Z1 + Z2. The increase in the thermal conductivity of the materials built into the perimeter cladding is largely dependent on their moisture and water state.

From energy efficiency point of view , it is necessary to consider the actual characteristics of the materials built into the casing. This means using the calculated values of the coefficient of thermal conductivity of individual materials built into the building envelope. One of the most important factors influencing the reliability of perimeter cladding is waterproofing and thermal properties.

By eliminating energy consumption for heating and reducing costs, these requirements are being radically tightened. Thermal technical standard STN 73 0540-2 + Z1 + Z2, applies to the design and assessment of structures and buildings with the required temperature of the indoor environment during their use. It lays down thermal technical requirements for construction and buildings, which ensure the fulfillment of the basic requirements for buildings.

In particular the fulfillment of the basic requirement for energy saving and heat protection and ensuring hygiene, health and environmental protection. It applies to heated new and refurbished buildings, but also to the assessment of existing buildings and to the implementation of alterations to completed buildings, building alterations, major renovations and changes in the use of buildings. The standard also applies to unheated buildings, or unheated parts of buildings, if a certain state of the indoor environment is required in them. When designing building structures and buildings, the fulfillment of the criterion is required:

1. Criterion of minimum thermal insulation properties of a building structure,
2. Hygiene criterion,
3. Air exchange criterion,
4. Energy criterion,
5. Criterion of the minimum energy performance requirement for buildings.

New buildings must meet the standardized requirements for the thermal properties of building structures and buildings as such. Major refurbished buildings must also meet standardized requirements. Where functional, technically and economically feasible, all building structures undergoing major renovation must meet at least the minimum requirements for energy-efficient buildings.

Building structures must meet the requirements for eliminating the risk of mold growth on their inner surface (hygienic criterion) and for avoiding condensation of water vapor in the building structure or on its inner surface. Fulfillment of these requirements ensures the demonstration of compliance with the basic requirements for hygiene and health protection.

Requirements for building structures and buildings take into account different levels of energy efficiency. Minimum requirements (maximum values), standardized (required), recommended and target recommended values of requirements expressing the tightening of thermal technical properties of building structures and buildings are set for the following levels:

1. Energy efficient building (minimum requirement),
2. Low energy building (required requirement)
3. Ultra-low energy building (recommended requirement),
4. Building with almost zero energy demand (target recommended requirement).

## CRITERION OF THE MINIMUM THERMAL INSULATION PROPERTIES OF THE BUILDING STRUCTURE

In the calculation it is necessary to determine the influence of thermal technical humidity of the building using the area of the heat exchange and thermal properties of individual building construction. The area of the heat exchange envelope is defined by the outer surface of the thermal insulation layer. The basic physical parameter by which we assess the individual fragments of the casing is the heat transfer coefficient $U$ (U-value) in W/(m².K) and the thermal resistance of the structure $R$ in m².K /W.

To meet the thermal comfort conditions and energy requirements, the walls, roofs, ceilings and floors of heated or air-conditioned residential and non-residential buildings in areas with the relative humidity $\phi_i \leq 80\%$, must have a heat transfer coefficient $U$, to meet the following condition:

$$U \leq U_N \tag{2.2}$$

where $U_N$ is the standard value

The heat transfer coefficient indicates the heat flux propagating from the indoor environment to the outdoor environment through 1 m² of the construction at a unit difference in temperature. We express the heat loss of an object by the heat transfer coefficient.

Tab. 2.1.1 Normalized values $U_N$

| Type of building construction | $U_N$ W/ (m². K) | | | |
|---|---|---|---|---|
| | Maximum value $U_{max}$ | Normalized value $U_N$ from 1.1.2013 | Recommended value from 1.1.2016 | Target recommended value $U_{r2}$ fro 1.1.2021 |
| Exterior wall and sloping roof > 45° | 0.46 | 0.32 | 0.22 | 0.15 |
| Exterior wall and sloping roof ≤ 45° | 0.30 | 0.20 | 0.15 | 0.10 |
| Ceiling over the outdoor environment | 0.30 | 0.20 | 0.15 | 0.10 |
| Ceiling under unheated space | 0.35 | 0.25 | 0.20 | 0.15 |

Normalized, minimum and recommended values of thermal resistance are given in STN 73 0540-2 + Z1 + Z2, where it applies that:

$$R \geq R_N \tag{2.3}$$

The thermal resistance of the building *R* and the heat transfer coefficient of the building *U* are determined according to STN EN ISO 6946. For structures with an open-air layer, the thermal resistance is determined from the layers of the structure located between the inner surface and the open-air layer of the structures.

For internal vertical and horizontal structures separating the rooms of different flats and flats with non-residential spaces with different heating and regulation regimes, a minimum indoor air temperature difference of 15 K is considered..

Heat transfer coefficient indicates the heat flux propagating from the indoor environment to the outdoor environment through 1 m$^2$ of the construction at a unit difference in temperature.

## HYGIENIC CRITERION

One of the most important criteria in building thermal engineering is to ensure a minimum internal surface temperature on the inner surface of the envelope. Walls, ceilings, roofs, and floors in areas with a relative humidity of $\phi_i \leq 80\%$ must have a temperature $\vartheta_{si}$ at each point of the internal surface, expressed in °C, which is safely above the dew point temperature and eliminates the risk of mold growth.

$$\vartheta_{si} \geq \vartheta_{si,\,N} = \theta si,80 + \Delta\vartheta_{si} \qquad (2.4)$$

where

$\vartheta_{si,N}$ is the lowest internal surface temperature to be determined for the least favorable interaction between the material composition and the geometry of the building structure, including thermal bridges,

$\vartheta_{si,80}$ critical surface temperature for the formation of molds, corresponding to 80% of the relative humidity in close proximity to the interior surface of the building at the interior air temperature $\vartheta_{ai}$ and the relative humidity of the interior air ϕi; for standardized indoor air conditions according to STN 73 0540-2 + Z1 + Z2 at indoor air temperature $\vartheta_{ai}$ = 20°C and relative indoor air humidity $\varphi$i = 50% is $\vartheta_{si,80}$ = 12,6 °C,

$\Delta\vartheta_{si}$ safety surcharge taking into account the method of heating.

## THERMAL BRIDGES AS A PART OF THERMAL INSULATION

The hygienic criterion is especially important when assessing the critical details that thermal bridges can create. Such critical details also occur in buildings with a low energy standard but also in buildings with nearly zero energy demand. The concept of the proposed building is not always simple. Every investor demands that his building be something exceptionally original. And a careless detail design can lead to the formation of thermal bridges (Buday, 2014), which directly affect the temperature of the inner surface of the building envelope.

Due to thermal bridges, the surface temperature on the inner surface of the perimeter cladding structure is reduced. Such a reduction in surface temperature can cause condensation on the surface which often leads to mold formation.

Such conditions are not acceptable for both residential and non-residential buildings, as they have a direct impact on human health and therefore need to be eliminated. Molds on the inner surface of structures are a serious hygienic deficiency (Chmúrny, 2003). They are tiny microorganisms - pathogenic fungi that form a tangle of fibers and resemble a velvet coating or cotton wool.

In recent years, several theories have emerged that assess the emergence of hygiene problems. They distinguish two phenomena: the first is the surface condensation of water vapor on the thermal bridge, and the second is the risk of mold under certain conditions. Molds germinate in conditions such as the presence of spores, the presence of oxygen and a suitable temperature. These requirements are always met by home interiors - spores occur in the outside air, oxygen is available and room temperatures are between 10 and 30 °C. As for the traditional view of surface condensation of water vapor as the cause of the formation and growth of fungi, it provides to be not entirely true and accurate.

Experiments have shown that the risk of mold arises before surface condensation of water vapor occurs. However, this risk can be ruled out if a minimum internal surface temperature is determined. For residential buildings, a design indoor temperature of 20 °C and a relative indoor humidity of 50% are considered. For these indoor environment parameters, the critical temperature for mold growth is 12.6 ˚C and the dew point temperature is 9.3 °C. Walls, roofs and floors are evaluated to prevent mold growth. Their temperature on the inner surface must be higher than the critical temperature for the formation of mold at any point.

In addition to these aspects, thermal bridges, cause an increase in heat loss and thus an increase in heating costs. Therefore, it is necessary to know all the possibilities of the types of thermal bridges (Fig. 2.1.2), which are part of the heat exchange shell, and to solve them already in the project part of the proposed objects. In addition to the usual typical thermal bridges, such as the connection of walls, roofs, floors and others, it is necessary to include modern atypical thermal bridges, which are not commonly found in simple buildings. These are mainly various anchoring elements, atypical geometries of individual structures, which delimit the heated space of buildings (Fig. 2.1.3).

The building envelope must protect the entire heated interior of the building so that the influence of thermal bridges is eliminated at all critical points or at least sufficiently eliminated. Thermal bridges can be created by changing the material or by changing the geometry of the structures.

In addition to the basic types of thermal bridges, new types are also being created using individual architectural modern designs. These are mainly anchoring elements of the perimeter cladding, or the ventilated facade applied to it. These anchoring elements can also be used for the local attachment of various elements such as railings, billboards, awnings, shelters, pergolas and such. Therefore, it is necessary to pay significant attention to this issue, as it has an impact on the indoor environment but also on the overall heat loss and thus on the overall energy efficiency of the buildings.

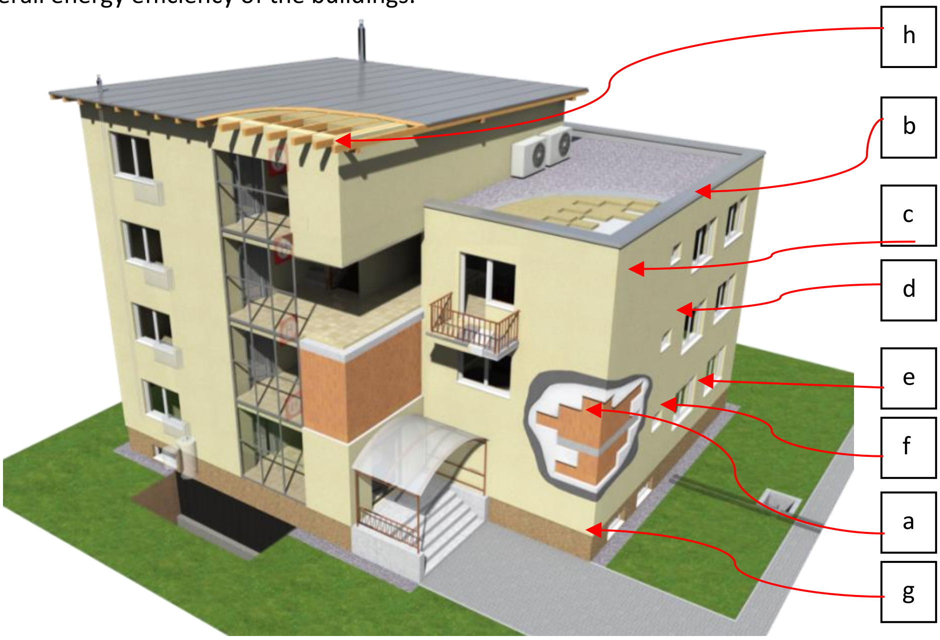


Fig. 2.1.2 Representation of common thermal bridges that occur on buildings: a) connection of two walls - nook, b) connection of flat roof - roof baluster, c) connection of flat roof - attic corner, d) lintels over the opening structure e) window sill of the opening structure, f) lining of the opening structure, g) detail at the plinth, h) detail at the connection of the sloping roof

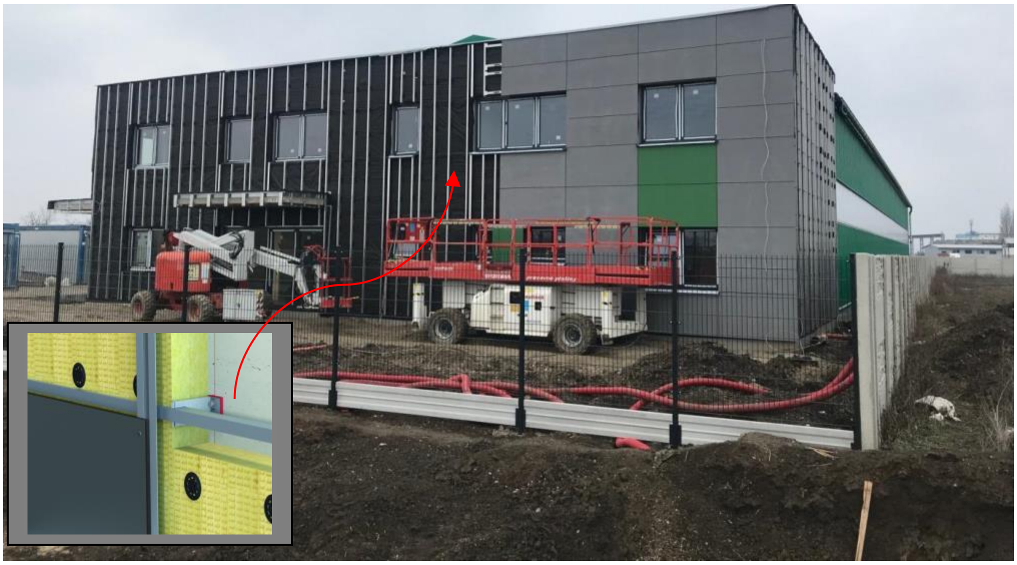

Fig.2.1.3 Representation of atypical thermal bridges that occur on buildings: a) anchoring of overhanging facades, which creates a 3D point thermal bridge

The temperature distribution in the structure and the heat flux through the structure can be calculated by iterative calculations, if the boundary conditions and structural details are known. For this purpose, the geometric model is divided by discretized elements of materials with specified homogeneous coefficient of thermal conductivity.
The temperature distribution is determined by an iterative calculation method or a direct solution method such as the finite element method. As a rule, it is not possible to display entire buildings with a single geometric model. In most cases, the building is divided by applying section planes. This division shall be made in such a way to exclude differences in the results of the calculation. When calculating using a 2-D method, it can determine the thermal permeability, heat flux and linear loss factor. The heat flux for two values of the edge temperature is determined per meter of length of the linear thermal bridge from the indoor environment to the outdoor environment and is calculated according to the following relation:

$$\Phi_l = L_{2D}(\theta_i - \theta_e) \tag{2.5}$$

where $L_{2D}$ is the thermal permeability determined from the 2-D calculation of the building structure separating the two considered environments.

For more than two environments with different temperatures (e.g., different indoor temperature or outdoor temperature), the total heat flux to or from the room is calculated according to the relation

$$\Phi = \sum_{ij} \left[ L_{2D,i,j}(\theta_i - \theta_j) \right]$$
(2.6)

where $L_{2D,i,j}$ is the thermal permeability determined from the 2-D calculation of the building structure between each pair of environments.

The linear loss factor Ψ of the considered linear thermal bridge separating the two environments is calculated according to the relation

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j l_j \tag{2.7}$$

where
$U_j$ is the heat transfer coefficient of the 1-D building structure separating the two environments,
$l_j$ the length of the 2-D geometric model on which the value applies $U_j$,
$N_j$ number of 1-D building structures.

Determination of thermal permeability and heat flux in 3-D calculation if only two environments with two different temperature values are known (e.g. one indoor and one outdoor temperature) and if the room or building is calculated using a three-dimensional simple model, then the total thermal permeability is obtained of the total heat flow of the room or building according to the relation:

$$\Phi = L_{3D,1,2}(\theta_1 - \theta_{e2}) \tag{2.8}$$

where $L_{3D,1,2}$ is the thermal permeability determined from the 3-D calculation of the building structure separating the two considered environments. The thermal permeability calculation from the 3-D calculation is determined by the relation

$$L_{3D,i,j} = \sum_{k=1}^{N_k} U_{k(i,j)} A_k + \sum_{m=1}^{N_m} \Psi_{m(i,j)} l_m + \sum_{n=1}^{N_n} \chi_{n(i,j)}$$
(2.9)

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$U_{k(i,j)}$ is the heat transfer coefficient for a part of a room or building,
$A_k$ area for which the value applies $U_{k(i,j)}$,
$\Psi_{m(i,j)}$ linear loss factor for part m of a room or building,
$l_m$ the length over which the value applies $\Psi_{m(i,j)}$,
$\chi_{n(i,j)}$ point loss factor for a part of a room or building,
$N_k$ number of heat transfer coefficients,
$N_m$ number of linear loss factors,
$N_n$ number of point loss factors.

The value of the point loss factor is calculated according to the relation

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i A_i - \sum_{j=1}^{N_j} \Psi_j l_j$$
(2.10)

where

$L_{3D}$ is the thermal permeability determined from the 3-D calculation of the 3-D building structure separating the two considered environments,
$U_j$ is the heat transfer coefficient of the 1-D building structure and separating the two considered environments,
$A_i$ area for which the value applies $U_i$,
$\Psi_j$ are linear loss factors,
$l_j$ the length of the geometric model over which the value applies $\Psi_j$,
$N_j$ number of 2-D building structures,
$N_i$ number of 1-D building structures,

When determining the point loss factor, it is necessary to state exactly which dimensions were used, because for some types of thermal bridges the values of the linear loss factor depend on this choice.
Part of the buildings are applied various architectural elements, which can be created with their fixed thermal bridges. It can be linear thermal bridges or point thermal bridges.
As an example, Fig. 2.1.4 shows an apartment building, where the designer designed a suspended grid of structure to support the plants. This grid eliminates overheating and complete the ecological architecture.

Fig. 2.1.4 View of an apartment building with a hanging wooden grate to hold the green

The grid of such a construction in terms of static properties is variable and sometimes it is necessary to use 5 pieces of anchoring elements up to 1m² (Fig. 2.1.5). Such a large number of load-bearing anchoring elements can have a significant effect on the heat losses of the object by means of point 3-D thermal bridges.

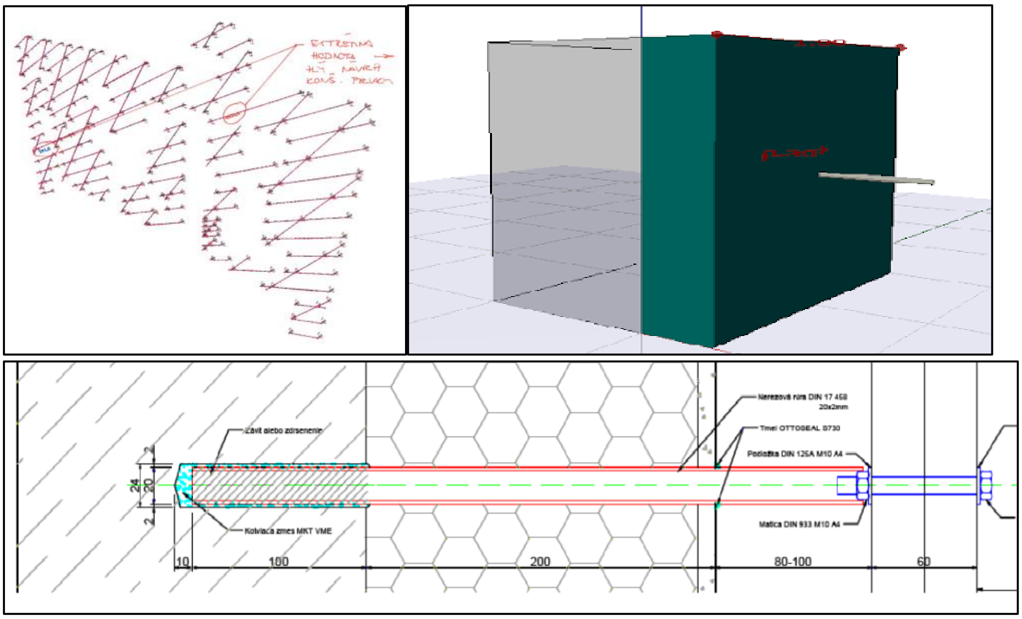



Fig. 2.1.5 View of the static diagram (grid of the anchorage of the supporting grate) on the facade of the apartment building and detail of the anchoring of the supporting grate (Ingeli, 2018)

This large number of anchoring elements has a significant effect on the heat transfer coefficient of the peripheral structure (Fig. 2.1.6). The following figure shows the dependence of the heat transfer coefficient of the perimeter structure on the number of load-bearing anchoring elements on the facade of an apartment building.

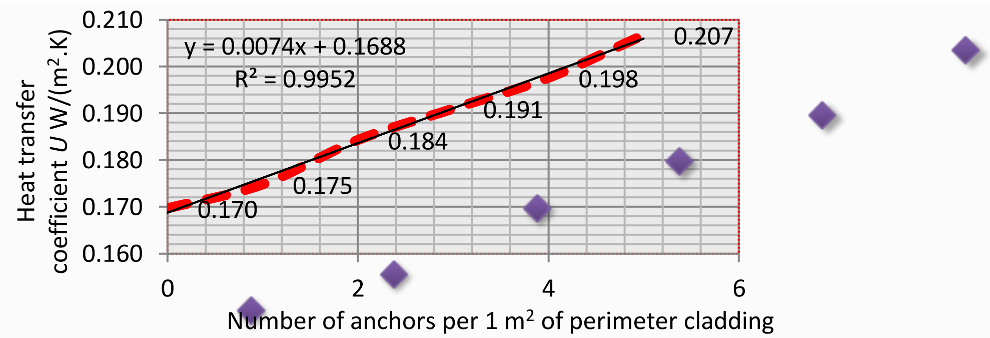



Fig. 2.1.6 Dependence of the wall heat transfer coefficient on the number of anchoring elements (Ingeli, 2018)

The next figure (Fig. 2.1.7) shows various point thermal bridges that occur in a residential building. It mainly applies to the most common points thermal bridges in the following Mechanical anchoring:

1. to the grate of the suspended ventilated facade,

2. to shelters, awnings and other overhanging structures,
3. of railings
4. of the roof covering,
5. of thermal insulation systems,
6. of rain gutters, common gutters,
7. of lightning conductor,
8. of antennas, satellites,
9. of solar panels to the roof structure,
10. of external blinds,
11. of transparent structures,
12. of atypical load-bearing steel structures,
13. other important design solutions of anchoring elements.

Fig. 2.1.7 Various examples of point thermal bridges

High thermal engineering requirements in buildings with almost zero energy demand lead to all critical details being already exactly resolved in the project part. We cannot talk only about the thickness of thermal insulation, but also about its application and in close proximity to the critical details that can form thermal bridges.

Currently, the problem of 3D details is coming to the fore, which may point to inappropriately designed atypical detail in buildings with rugged geometry and atypical architecture.

One such atypical detail is the connection of two not-orthogonal walls (Fig. 2.1.8). Such a complex detail is not sufficient to be considered only by 2D method but a 3D method is needed. This detail leads to problems with connection to other adjacent structures (Ingeli 2018).

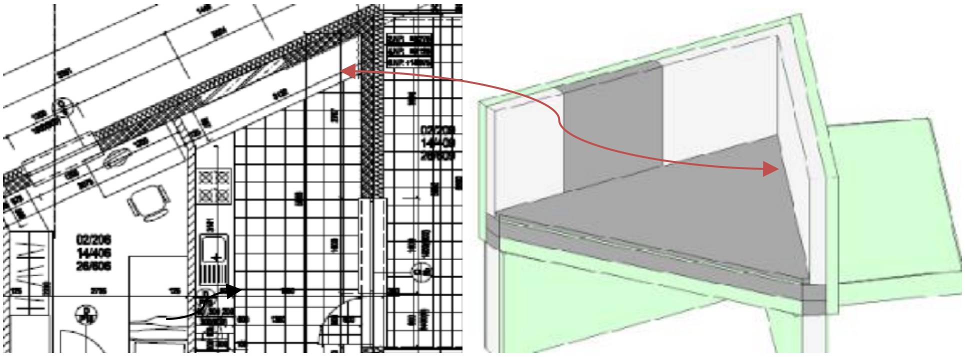


Fig. 2.1.8 Analyzed detail of the connection of two not-orthogonal walls and the ceiling structure

Such a detail, which creates an architectural element in the building, has a significant effect on reducing the internal surface temperature and can cause unhygienic conditions for living in the building (Fig. 2.1.9). It can be seen from the given figure that neither the measured values nor the calculated ones meet the current hygienic requirements.

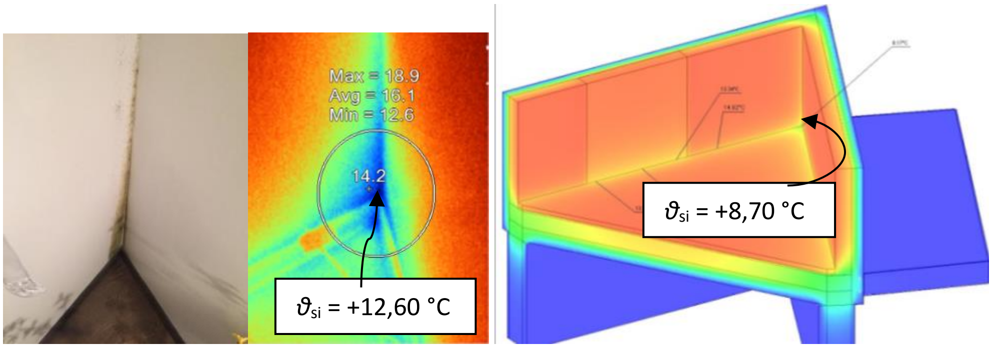



Fig. 2.1.9 Thermography measurement and 3D simulation of detail solution

At the end of this chapter it can be said that it is not possible to consider buildings with almost zero energy demand only as a fragment with heat dissipation 1D, but an exact analysis of all elements that are part of thermal insulation applied in the perimeter cladding is needed. Such a same problem is also part of flat roofs with mechanical anchoring. Anchors as well as changes in geometry (Fig. 2.1.10) and changes in materials create inhomogeneous structures. The following figure shows a critical detail of the connection of a reinforced concrete column to a reinforced concrete ceiling above the exterior. The column forms a thermal bridge. While the calculation of 2D critical detail satisfies (2.19), using the 3D method it can be seen that the requirement for a hygienic criterion is not met. In this case, it is also a building with almost zero energy requirements.

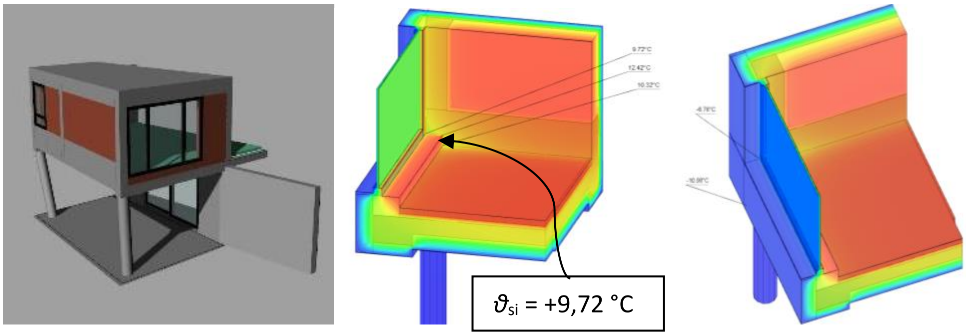



Fig. 2.1.10 Assessment of 3D critical detail of the connection of the column to the ceiling above the exterior

In most cases, inhomogeneous structures are thermal bridges and their thermal properties can be significantly reduced (Kosny 2001). Inhomogeneous structures, which are composed of several substances with different thermal properties, represent a thermal bridge caused by a change in the thermal properties of the peripheral shell. Thermal bridges create materials with high thermal conductivity and can reduce the local thermal resistance of the perimeter shell. This is especially important for thicker thermal insulation thicknesses (Mao 1997).

In some cases, thermal bridges can account for up to 30% of final energy consumption (Theodosiou 2008, Spiekman 2002). The accumulation of materials is also of great importance for thermal bridges (Larbi 2005). Simplified calculation of inhomogeneous structures, where the thermal resistance for the infill and frame is calculated, is acceptable for wooden frame structures. However, it cannot be used for many of the more complex technologies that are introduced in the market. In addition, the architecture is becoming more complex and the result is an increase in the use of frame elements (Kosny 2002). Studies conducted for the California Energy Commission (Carpenter 2003) have shown that the frame factor (area of opaque structures where the frame is made of solid wood) for the walls of residential buildings is nearly 27%. The resulting value of thermal resistance of frame structures, whose thermal resistance at the place of thermal insulation filling is $R$ = 2.6 m$^2$W/K is in the range from 1.5 - 1.6 m$^2$W / K.

By including the frame structure, the thermal resistance is reduced by 35 to 40%. This would mean that houses built in this way would require approximately 10 - 12% more energy than using a simplified calculation, without including frame structures (Kosny 2004). When creating the concept of buildings with almost zero energy demand, it is necessary to meet the thermal requirements of the individual fragments that make up the heat exchange envelope.

In addition to these requirements, it is necessary to address individual critical details that are the potential for future failures. It is nice to live in a building with almost zero energy requirements, but if hygiene requirements are not met, the building is uninhabitable. Thus when creating the concept of the building, it is necessary to try to design a simple geometry without unnecessary critical details.

### 2.1.2 THERMAL INSULATION MATERIALS

The main purpose of thermal insulation materials is to reduce the thermal conductivity of the structure and eliminate thermal bridges in buildings. As regards the material base, in the past, mainly plant-based or animal-based materials were used (Tables 2.1.2 and 2.1.3). Synthetic fiber materials are currently on the market and are widely used.

Tab. 2.1.2 Distribution of thermal insulation by shape (Rouseková, I, 2009).

| Thermal insulation | Material base | Form | Raw material base |
|---|---|---|---|
| Fiber | mineral fibers | mats, mattresses, soft boards, hard boards | basalt wool, glass wool |
| Shaped | foam plastics, expanded plastics | board products, lightweight concrete fittings | polystyrene, polyurethane, polyvinyl chloride, polyethylene |
| Loose | granular materials | granulars | expanded perlite, granular expanded plastics, porous rocks, crushed foam glass, lightweight porous aggregates |

Tab. 2.1.3 Classification of thermal insulations according to the material base from which they were made (Rouseková, I, 2009).

| Material base | Types |
|---|---|
| Inorganic substances | mineral fibers, foam glass, expanded perlite |
| Organic substances | lightweight plastics - polystyrene, polyurethane, polyethylene, cork, wood wool, paper |
| Combined substances | combinations of organic and inorganic substances |

In addition to the thermal technical properties, thermal insulation also has sufficient acoustic properties as well as accumulation properties, which are used for protection against overheating of indoor living spaces. The current trend is the use of thermal insulation based on mineral fibers or expanded plastics. These materials are also widely used in buildings with almost zero energy requirements. To a large extent, the price is mainly decisive when deciding on the choice of thermal insulation material. But the company's priority will be to use materials that will not burden our environment throughout their lifetime. Therefore, the company needs to focus on green buildings with almost zero energy needs, as these materials are more friendly and create a sustainable architecture.

## CURRENT THERMAL INSULATION MATERIALS

This category includes such materials that are currently commonly available and mostly minimize their thermal conductivity by their structure, where heat conduction predominates mainly in heat losses. The following table (Table 2.1.4) describes the individual selected materials that are justified not only in conventional architecture but also in sustainable architecture. Table 2.1.5 shows materials that are currently widely used in low-energy buildings as well as in buildings with almost zero energy demand.

Tab. 2.1.4 An example of various thermal insulation materials also used for sustainable architecture

| Thermal insulation | Thermal conductivity | Main benefits | Main disadvantages |
|---|---|---|---|
| Wool (www.naturwool.sk, www.deamwool.sk) | 0,034 – 0,042 W/(m.K) | receives air humidity | lower fire resistance |
| Cannabis seed (www.alfanatur.sk), (Chybík, 2009) | 0,040 – 0,044 W/(m.K) | suitable for allergy sufferers | limited availability of raw material |
| Flax seed (www.izolater.sk) | 0,040 – 0,043 W/(m.K) | resistant to fungi | lower mechanical resistance |
| Straw (www.createrra.sk, www.zelenarchitektura.sk) | 0,041 – 0,046 W/(m.K) | low price very low | low resistance to mold in the presence of moisture |
| Cork (www.korok.sk) | 0,041 – 0,046 W/(m.K) | long life | variable availability |
| Kokos (www.baunetzwissen.de) | 0,045 – 0,050 W/(m.K) | long life | variable availability |
| Cellulose (www.drevosen.sk, www.vuno.sk) | 0,038 – 0,040 W/(m.K) | Favorable phase shift | professional installation |
| Fibreboard insulation (www.tepore.sk) | 0,038 – 0,042 W/(m.K) | high strength | high energy consumption in the production of panels |
| Textile insulation (www.sk-tex.com) | 0,035 – 0,041 W/(m.K) | low energy consumption, | non-adapted legislation for the |

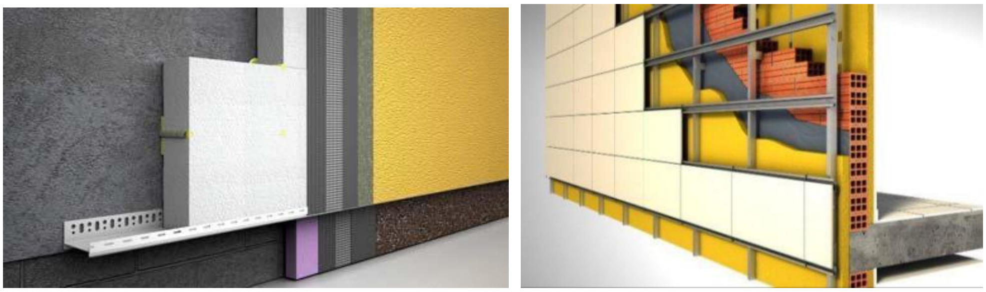
| | | | |
|---|---|---|---|
| | | | Slovak market |

Tab. 2.1.5 An example of various commonly available thermal insulation materials used in buildings with almost zero energy demand

| Thermal insulation | Thermal conductivity | Main benefits | Main disadvantages |
|---|---|---|---|
| Glass wool | 0,036 – 0,044 W/(m.K) | non-combustible material | in case of contact with water it loses its insulating properties |
| Stone wool | 0,037 – 0,045 W/(m.K) | resistant to high temperatures | in case of contact with water it loses its insulating properties |
| Expanded polystyrene | 0,035 – 0,039 W/(m.K) | low price,<br>high compressive strength | diffusely sealed material, petroleum product |
| Extruded polystyrene | 0,033 – 0,036 W/(m.K) | non-absorbent material,<br>good mechanical properties | more expensive than EPS, a petroleum product |
| PIR boards (www.isover.sk) | 0,020 – 0,028 W/(m.K) | non-absorbent material,<br>with applied Al. foil favorable to overheating | petroleum product, |

In terms of the application directly to the building, we know two technologies. It is a contact thermal insulation system ETICS or a suspended ventilated facade (Fig. 2.1.11). Both technologies can be part of buildings with almost zero energy demand. Each has its own advantages and disadvantages. While the contact thermal insulation system is more cost-effective, it is recommended to be used in diffusely closed compositions. Thus, in such compositions, PVC-based thermal insulation, which has a higher diffusion resistance, is used as much as possible.

Ventilated systems use thermal insulation with low diffusion resistance, such as mineral wool, as it is a diffusely open structure that is ventilated on the outer surface. When using fiber thermal insulation, it is necessary to provide protection against rain during implementation, as the moisture itself in such materials can impair their mechanical and significantly also the thermal properties. The effect of moisture on thermal insulation is described in the next chapter.



a) b)

Fig. 2.1.11 View of thermal insulation systems a) - contact thermal insulation system ETICS, b) - ventilated facade

## PROGRESSIVE THERMAL INSULATION MATERIALS

One of the progressive materials is vacuum thermal insulation. It consists of a microporous core from which air is exhausted and which is completely airtight and sealed in a thin container. This achieves excellent thermal conductivity in the thinnest design for solving specific insulation problems.

With its declared thermal conductivity $\lambda_D$ = 0.007 W/(m.K), the product achieves up to five times higher insulation capacity compared to other, traditional insulation materials. Properly installed and protected against damage and penetration, the product provides reliable and long-lasting thermal insulation throughout the life of the building. Vacuum insulation panels provide a solution for cases associated with lack of space when dealing with critical details. In terms of recycling, more than 90% of the product can be recycled (by weight).

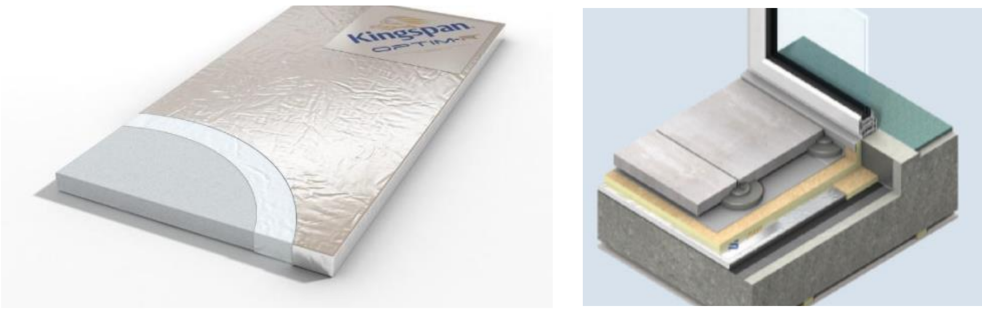



Fig. 2.1.12 View the vacuum thermal insulation Optimal - R and the possibility of applications directly in the critical detail ([www.kingspan.com](www.kingspan.com))

Vacuum insulation panels contain as a rigid network structure composed of clusters of silica particles ($SiO_2$) of Nano metric dimensions. This spatial, very fine network is known as an aerogel.

Another important component is an airtight and mechanically rigid package with high thermo-reflection. This will enable complete and permanent extraction of air from the $SiO_2$ filling, as well as permanent, almost complete shading of the radiant component of heat sharing and, finally, trouble-free handling of the panels during construction. The panels are manufactured in the dimensions of building insulation boards, their thickness is small, from 2 to 8 cm. They reach the coefficient of thermal conductivity from $\lambda$ = 0.004 - 0.007 W / (m.K). Highly and finely porous and at the same time rigid panel filling, also known as aerogel, has undergone concentrated development.

A very finely dispersed silica called fumed silica has been introduced, which is formed by the flame hydrolysis of tetrachlorosilane at high temperatures up to 1500 ° C. The mass has a very fine microstructure resembling a spatial network with meshes of a mean size of about 70 nm (nanometers). The advantage of this structure arises when we realize that the mean free path of air molecules (between two collisions) is also around 70 nm at atmospheric pressure. The conduction of heat in the air takes place mainly by mutual collisions of air molecules, during which they exchange energy (more precisely the quantities of vibrational energy - phonons) and, as part of a large statistical set of all air molecules, conduct heat. However, a large part of them will remain isolated in the cells of the Nano porous $SiO_2$ network and can exchange energy with free ones with only a small statistical probability.

Another progressive material is foam glass, which is mainly used in the use of floors in the field, as well as in new construction and reconstruction of the building. It is made of special aluminosilicate glass, ground to a powder and mixed with very fine carbon dust. The mixture is heated to approx. 1000 ° C in steel molds in a tunnel kiln. In this process, the glass is melted, at the same time the carbon is oxidized to Co2 gas, which then forms a foam from the melt and increases its volume. The final dimension did not stabilize until cooling to the usual temperature of about 20 ° C.

The new material contains small closed bubbles, which thanks to its structure the material is completely non-flammable and vapor-tight. This material is mainly used in energy-efficient or passive houses. Another application is the insulation of mobile and walkable roofs with very high compressive stress in industrial plants, civil infrastructures.

The coefficient of thermal conductivity of foam glass is 0.04 to 0.048 W / (m.K). It is most commonly used as a base for floors in the field and as thermal insulation but also as a drainage of a building. However, it is also necessary to mention that its properties are also affected by ground moisture and water, and therefore it is necessary that the moisture and groundwater are drained from the foam glass layer.

Fig. 2.1.13 Application of foam glass during the foundation of the building

Another progressive thermal insulation material is reflective thermal insulation. The intention of most thermal insulations is to limit heat transfer by conduction. In this way of limiting heat transfer, significant progress can be seen in both the design and verification of the thermal properties of these products [Yücel et al., 2003]. The principle of reflective insulation is based on the reflectivity of radiative heat. Each body, if its temperature is greater than 0 K (-273.15 °C), emits electromagnetic waves of different wavelengths in all directions, and in addition can reflect, absorb and transmit this radiation.

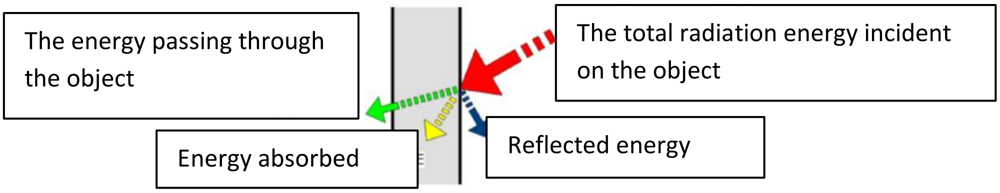



Fig. 2.1.14 Scheme of distribution of radiant energy incident on the body surface (Kalánek, 2020)

Electromagnetic radiation propagates through the environment at a speed that depends on the type of environment. This transfer does not require a material environment and is also possible in a vacuum space. The speed of radiation propagation in vacuum has a value of approx. 3.108 m/s. An important quantity describing the radiation of the body is emissivity. Emissivity is defined as the ratio of the radiation intensity of a real body to the radiation intensity of an absolutely black body with the same temperature.
This statement is described in Kirchhoff's 2nd law, which states that an object is as perfect a radiant as it is capable of absorbing, and therefore the emissivity of the object's surface is equal to the absorption. The emissivity can thus reach values from 0 to 1, and its value

depends mainly on the structure of the surface material, the temperature or wavelength and the direction of radiation. Emissivity values can be divided [Pavelek, 2007]:

1. spectral emissivity-emissivity value at a certain wavelength of radiation,
2. band emissivity - effective value in the considered wavelength band,
3. total emissivity - characterizes the total radiated power over all wavelengths.

Therefore, a material with a high thermal radiation reflectance, i.e. a surface with a very low emissivity value, is used as the outer reflective layer. Reflective insulation is defined as thermal insulation consisting of one or more low emissivity surfaces that delimit one or more air cavities [RIMA International, 2002].

The use of reflective insulation has appeared in the literature since the beginning of the twelfth century. A comprehensive review was cited in 1989 by Goss and Muller [Goss, 1989] many references from 1900 to 1989 [Šťastník et Vala, 2014]. The publication [Nash et al., 1955] and [Fricker, 2011] describe typical values of thermal resistance of selected compositions and e.g. in [Robinson et Powell, 1954], [Robinson et al., 1957], the results of hot box pickling for systems with reflective insulation were published. These data then formed the basis of the thermal resistance values contained in the ASHRAE Fundamentals manual [1972].

At present, significant progress can be seen in the use of reflective insulation in roof structures [Craven et Garber-Slaght, 2011]. Reflective insulation is defined as thermal insulation consisting of one or more low emissivity surfaces that define one or more air cavities. In order to maintain the highest possible ratio of radiation to other heat transfer components (conduction and flow), it is important that the core material of the reflective insulation is as large as possible made of air.

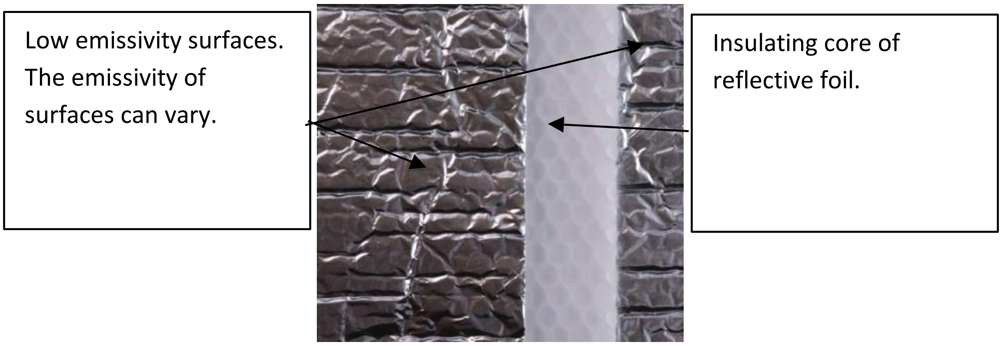



Fig. 2.1.15 Scheme of composition of reflective insulation

The material forming the core of the reflective insulation is simply divided into:
1. polyethylene foam (the most common type 1 product),
2. bubble foil - air-filled plastic bubbles (product type 2),
3. foam or cotton wool (most often a sandwich - a product of type 3).

The reflective / low-emission surface can be designed mainly in two basic ways:
1. Low-emissivity coatings, sprays, metallization (e.g. vacuum plating),

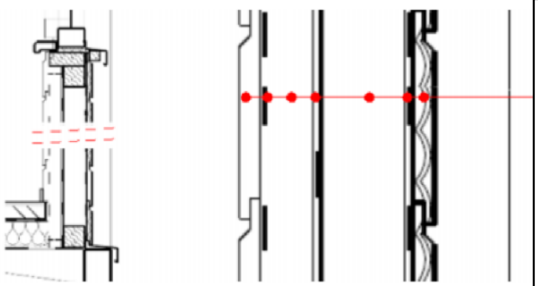
2. Low emissivity foils.

We distinguish 4 basic types of reflective insulation in the following table.

Tab. 2.1.6 Distribution of reflective insulation

| Type | Description |
|---|---|
| Type 1 | This type of product has a regular structure (parallel surfaces) or is compressible into this geometry without changing the thermal properties. Surface notches should be less than 2 mm. And the insulation thickness is greater than 2 mm. |
| Type 2 | This type of product has a regular structure (parallel surfaces) or is compressible into this geometry without changing the thermal properties. Surface notches should be less than 5 mm. |
| Type 3 | This type of product does not have a regular structure (parallel surfaces), because it is compressible into this geometry with a change in thermal properties. Surface notches should be larger than 5 mm. |
| Type 4 | It is a thin coating (sheet) that is thinner than 2 mm. Itself has no significant thermal resistance. |

The following figure shows the application of a reflective foil in the perimeter wall of a wooden building.



- wood 10mm thick
- vapor barrier with reflective surface
- air layer, thickness 46mm
- 8 mm thick insulation made of lightweight PE with a reflective surface
- air layer 80mm thick
- insulation hr. 8mm made of lightweight PE with reflective surface
- wood 10mm thick

Fig. 2.1.16 Section of the wall structure with applied reflective insulation (Kalánek, 2016)

The application of reflective insulation without adjacent air layers is irrelevant. In addition to the thermal insulating properties of the reflective insulation core, the thermal insulating properties of the adjacent air layers were also monitored within several experimental delays at steady state. Several experimental measurements and their outputs have shown that the thermal resistances of the air layers are not negligible in comparison with the thermal resistance of the core of the reflective insulation product. For this reason, when using reflective insulation, it is necessary to ensure their application in building structures always in connection with the air cavity.

When applying flat roofs or sloping roofs, we encounter thermal insulation material marked PIR. The PIR material consists of a combination of urethane and isocyanurate bonds. In contrast to the PUR material, in addition to the excess isocyanate, polyester polyols are also used in the production of PIR, which fit into its annular structure. Insulation made of rigid polyurethane foam, now produced under the name PIR insulation, are insulations with the highest thermal resistance at a minimum thickness.
Insulation boards made of hard PIR foam, with non-laminated aluminum foil, are used when used as over rafter thermal insulation.
The coefficient of thermal conductivity of such PIR boards ranges from 0.022 W/(m.K) to 0.028 W/(m.K). Their values vary according to the thickness of the PIR thermal insulation. The greater the thickness of the thermal insulation, the lower the coefficient of thermal conductivity.

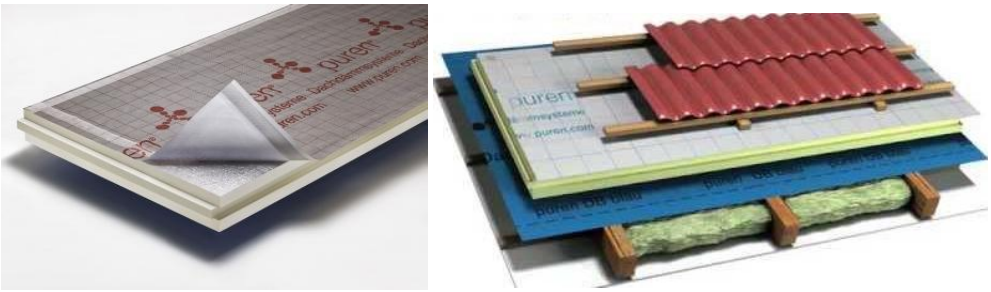



Fig. 2.1.17 Application of PRI board with integrated aluminium layer in the rafter system

### 2.1.3 THE INFLUENCE OF HUMIDITY ON THERMAL TECHNICAL PROPERTIES OF THE BUILT-IN MATERIALS

At present, the priority, when renovating buildings or new constructions, is to design structures so that the building has low energy consumption or is classified in the required energy class. In some cases, this requirement becomes a priority and other required functions of the perimeter shell are not addressed. Therefore, it is necessary to approach the design of the perimeter cladding with caution and to take into account in the design all factors that affect the structural and physical properties of the cladding.
In addition to the thermal properties, it is necessary to design the perimeter cladding also in terms of humidity regime. If the individual layers of the perimeter shell contain moisture, their thermal parameters, defined by the coefficient of thermal conductivity $\lambda$ v W/m. K, are completely different from those taken into account in the design.
Moisture content increases thermal conductivity. Figure 2.1.18 shows the dependence of the thermal conductivity coefficient on the mass moisture of selected materials which can be linear or exponential. The coefficient of thermal conductivity is unstable. Its size depends on the humidity, temperature and pressure of the material. Therefore, it is always necessary to

ensure during each design that the structure is designed so as to limit as much as possible the increase in moisture in the individual materials that are built into the composition.

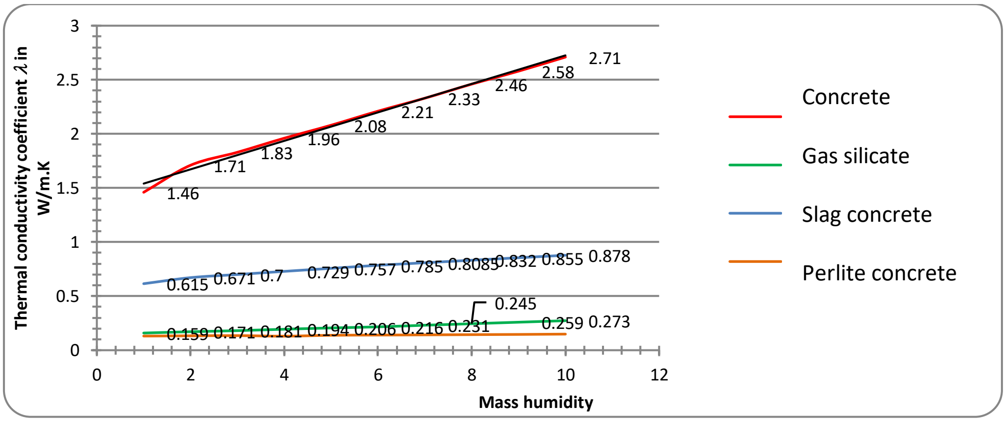


Fig. 2.1.18 Dependence of conductivity coefficient on mass moisture on selected materials (Mrlík, 1985)

The increase in thermal conductivity also depends on the state of water that is in the individual layers (Tab.2.1.7) The thermal conductivity of ice is about 4 times greater than the thermal conductivity of water. If all the pores of the material are filled with ice, the coefficient of thermal conductivity increases rapidly. The higher the humidity, the more water turns into ice, and the higher the value of the thermal conductivity of the substance increases.
This phenomenon can also damage individual layers in the designed structure. This is mainly due to a change in volume. Therefore, it is necessary to correctly design the composition of the roof cladding so that moisture does not accumulate in the individual layers of the roof cladding during the function of the roof cladding. The thermal conductivity of water in all states also depends to a large extent on the temperature. Temperature influences the coefficient of thermal conductivity of dry materials as well, so that with increasing temperature its value increases in the range of positive as well as negative temperatures. In practice, building materials almost never occur in the dry state. Moisture is characterized by the presence of chemically unbound water in the substance. Moisture is the presence of water in a gaseous, liquid or solid state. We characterize the moisture of the substance by mass and volume moisture. Mass moisture indicates the percentage by weight of evaporated water and the weight of dry material.

Tab. 2.1.7 Thermal conductivity of water in different states (Mrlík, 1985)

| The state of water | Thermal conductivity $\lambda$ v W/ (m.K) |
|---|---|
| Water vapor | 0.024 |
| Liquid form | 0.59 - 0.69 |

| | |
|---|---|
| Solid state (ice) | 2.4 |

The basic moisture properties of substances include absorbency, capillarity and equilibrium humidity. Absorbency is the amount of water that the dried material receives when completely immersed in water per unit time. Capillarity is the rise of water in a porous substance due to capillary elevation above the ambient level with which the test material came into contact. Equilibrium humidity is the amount of moisture that a material receives from air when exposed to constant temperature and humidity conditions. In practice, it can also be found under the name of hygroscopic moisture, it is the ability to absorb and at the same time maintain moisture in the material. In order to determine the effect of relative humidity on the amount of water in the materials, it is necessary to expose the material to the gradual action of relative humidity from the lowest (20%) to the highest value (95%), in a certain time interval. Humidity increases until equilibrium sorption humidity is reached (material and air have the same humidity). We have an isotherm of sorption. Otherwise, if we expose the sample from the highest humidity to the lowest, we speak of the desorption isotherm (Trnková, 2018). Sorption of materials is a phenomenon that occurs when a material has a lower pressure than the environment. The material thus receives water vapor from the air. We call this moisture sorption moisture. The degree of sorption of building materials is expressed by the moisture content in%. It is the result of a dynamic balance between air and material. Desorption (the opposite of sorption) occurs when the water vapor pressure in a material is higher than in the environment. In such circumstances, the material releases moisture. The relationship between relative humidity and equilibrium humidity is expressed by sorption isotherms. The sorption isotherm is a curve expressing the process of sorption and desorption of water vapor in the material. The sorption isotherm occurs when a sample exposed to a constant temperature in an environment with higher relative humidity has taken up water. Otherwise, if the material dries due to lower relative humidity in the environment, a desorption isotherm is formed (Mrlík, 1985). The following tables show the equilibrium humidity dependences for different relative humidities and the dependences of the thermal conductivity of materials on moisture.

Tab. 2.1.8 Detected values of measured equilibrium humidity for selected thermal insulation

| Thermal insulation | | Equilibrium humidity (% hm) At different relative humidity (%) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 20 | 50 | 80 | 95 |
| Pressed straw board | Sorption | 0 | 1,21 | 1,66 | 5,61 | 15,71 |
| | Desorption | 0 | 3,7 | 0,61 | 8,02 | 15,71 |
| Steico fiberboard | Sorption | 0 | 0,3 | 3,18 | 8,6 | 30,03 |
| | Desorption | 0 | 3,48 | 0,66 | 7,93 | 30,03 |
| Flax fiber insulation | Sorption | 0 | 0,34 | 0,41 | 6,82 | 17,05 |
| | Desorption | 0 | 5,79 | 2,49 | 2,71 | 17,05 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Hemp insulation board | Sorption | 0 | 0,05 | 2,61 | 6,71 | 14,52 |
| | Desorption | 0 | 0,55 | 2,34 | 6,9 | 14,52 |
| Mineral wool | Sorption | 0 | 2,027 | 1,92 | 1,89 | 1,98 |
| | Desorption | 0 | 1,62 | 1,79 | 1,81 | 1,98 |
| Extruded polystyrene | Sorption | 0 | 0 | 0 | 0,02 | 0,23 |
| | Desorption | 0 | 0,12 | 0,15 | 0,12 | 0,23 |

Tab. 2.1.9 Determined values of measured thermal conductivity for selected thermal insulations

| Thermal insulation | | Coefficient of thermal conductivity in W / (m.K) at different relative humidity | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 20 | 50 | 80 | 95 |
| Pressed straw board | Sorption | 0,099 | 0,096 | 0,154 | 0,153 | - |
| | Desorption | 0,099 | | | | |
| Steico fiberboard | Sorption | 0,038 | 0,055 | 0,057 | 0,069 | 0,082 |
| | Desorption | 0,038 | 0,059 | 0,059 | 0,069 | 0,082 |
| Flax fiber insulation | Sorption | 0,039 | 0,054 | 0,059 | 0,0639 | 0,075 |
| | Desorption | 0,039 | 0,056 | 0,057 | 0,057 | 0,075 |
| Hemp insulation board | Sorption | 0,042 | 0,055 | 0,064 | 0,076 | 0,077 |
| | Desorption | 0,042 | 0,056 | 0,061 | 0,076 | 0,077 |
| Mineral wool | Sorption | 0,035 | 0,046 | 0,051 | 0,052 | 0,053 |
| | Desorption | 0,035 | 0,047 | 0,049 | 0,052 | 0,053 |
| Extruded polystyrene | Sorption | 0,035 | 0,039 | 0,041 | 0,047 | 0,048 |
| | Desorption | 0,035 | 0,040 | 0,044 | 0,045 | 0,048 |

As can be seen from the previous results given in the tables, which were processed at the Faculty of Civil Engineering, humidity has a significant effect on the coefficient of thermal conductivity. Therefore, in practice, it is always necessary to take into account the design values of the thermal conductivity coefficient. In addition to the change in thermal conductivity, the structure also changes the structure of the material due to moisture, especially in fiber insulation.

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